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METHOD AND APPARATUS FOR REDUCING COMBUSTION RESIDUES IN EXHAUST GASES

PRIORITY CLAIM

[1] This application claims priority to PCT Application No. PCT/EP2003/051113 filed December 30, 2003, which claims priority to Italian Patent Application Nos. MI2003A000571 filed March 21, 2003, MI2003A002179 filed November 12, 2003, and MI2003A002180 filed November 12, 2003, which are incorporated herein by reference.

FIELD OF THE INVENTION

[2] The present invention generally relates to the field of reduction of environmental pollution, particularly air pollution caused by the emissions of apparatuses, such as internal-combustion vehicle engines (Otto cycle, Diesel cycle), burners for heating systems, generators of vapor for electric power generation plants, whose operation involves the combustion of fuels, for example fossil fuels such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, coal, wood and similar. In particular, the invention relates to a method, and a related apparatus, for reducing combustion residues, particularly noxious pollutants, in exhaust gases.

BACKGROUND OF THE INVENTION

[3] The problem of environmental pollution is nowadays very felt by people and governments, and efforts are constantly made to find out solutions for reducing the various human activities impact on the environment .

[4] In particular, air pollution caused by the emissions of apparatuses such as internal-combustion vehicle engines (based on Otto cycle or Diesel cycle), burners for heating systems, steam boilers for electric power plants, whose operation involves burning fuels, particularly fossil fuels, such as hydrocarbon fuels or hydrocarbon containing fuels like petroleum, including

natural gas, and coal, was probably the first aspect to be recognized in the more general problem of environmental pollution.

[5] Although the problem of massive emissions of pollutants into the atmosphere was starting with the invention of the steam-power machine at the industrial revolution dawn, it was the impressive growth of circulating vehicles in urban areas in the decades after the second world war which brought the problem in foreground.

[6] Thus, on one side, measures restricting vehicles circulation were and are still adopted when the situation reaches at crisis level. On the other side, and in parallel, under the pressure of governments and of the public opinion, vehicle manufacturers and research institutes have started to study solutions for the problem of emissions of noxious pollutants by internal-combustion engines.

[7] For example, in the European Union geographic area the maximum levels of tolerated vehicles emissions have been set by law, and a system of classification has been introduced for vehicles engines based on their respective level of pollutants emissions, in particular, since January 2001, the previous standards known as EURO1 (introduced in 1987) and EURO2 have been replaced by the more restricted standard EURO3, which will be replaced by the even stricter standard EURO4 since January 2006. This classification imposes that vehicles falling in the lower classes are not allowed to circulate in case restrictive measures are issued by governments or public administrations in consequence to a crisis situation approaching.

[8] The main pollutants present in exhaust gases of internal-combustion engines, particularly of Diesel type, are carbon oxide (CO), carbon dioxide (CO_2), uncombusted hydrocarbons (HC), various nitrogen oxides (NO_x), and Particulate Matter (PM), especially carbon particulate.

[9] Similar substances are found in the exhaust gases of heating implants and, more generally, of any apparatus whose action involves the combustion of fuels, particularly fossil fuel.

[10] Each one of the above mentioned substances is noxious to human health for one or more reasons, causing cancer, lung disease and others. Thus, it would be extremely important to reduce as far as possible, or possibly eliminate, these substances from the exhaust gases.

SUMMARY OF THE INVENTION

[11] In view of the state of art above outlined in the foregoing, an object of the present invention has been to provide an effective solution to the pollution problem due to the internal combustion engines emissions and, more generally, to the problem of environmental pollution due to the emissions of any apparatus whose action involves the combustion of fuels, particularly but not limitatively fossil fuel, such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, and coal, or even wood, and generally any fuel that can be used in a combustion process.

[12] The Applicant has found that noxious pollutants (gases, dust, particulate material, particularly carbon particulate) which are normally produced by apparatuses whose operation involves the combustion of fuel, particularly but not limitatively fossil fuel, such as internal combustion engines and burners of heating systems of buildings, can be substantially reduced, not to say completely eliminated, if the exhaust gases are submitted to a treatment that involves a post-combustion of the exhaust gases, and particularly a radiant post-combustion, ignited by submitting the exhaust gases to radiant energy, providing for a relatively fast increase of the exhaust gases temperature to a value in a properly chosen temperature range, adapted to essentially destroy the pollutants present in the exhaust gases.

[13] For the purposes of the present description, by radiant combustion there is intended a combustion process that is ignited by a heat

source not involving the presence of a flame, but irradiating electromagnetic energy, particularly in the range of wavelengths from InfraRed (IR) to UltraViolet (UV).

[14] In other words, the Applicant has found that by submitting the exhaust gases to radiant energy in a suitably designed radiant reactor, wherein the gases are subjected to a relatively fast increase of their temperature, up to a value in the properly chosen temperature range, a substantially perfect post-combustion is achieved, where, for the purposes of the present invention, by "perfect" there is meant a post-combustion that allows substantially the elimination of any noxious component or substance, such as CO, CO_2, HC, nitrogen oxides, PM, in particular carbon particulate, sulphur oxides, from the exhaust gases that are originated by the combustion of fuels.

[15] According to a first aspect of the present invention, a method for reducing pollutants in exhaust gases generated from the combustion of fossil fuel as set forth in the appended independent method claim 1 is thus provided.

[16] Summarizing, the method comprises treating the exhaust gases before releasing them in the environment, by performing a post-combustion process according to which the exhaust gases are submitted to radiant energy so as to increase a temperature thereof to a value sufficient to ignite self-combustion.

[17] According to a second aspect of the present invention, there is also provided an apparatus for reducing pollutants in exhaust gases generated from the combustion of fossil fuel, as set forth in the appended independent apparatus claim 16.

[18] In brief, the apparatus comprises means for treating the exhaust gases before releasing them in the environment, such treating means comprising a radiant combustion chamber wherein the exhaust gases are caused to pass through, so as to be submitted to radiant heat for increasing a

temperature thereof to a value sufficient to ignite self-combustion, thereby a post-combustion process of the exhaust gases is performed before releasing them in the environment.

BRIEF DESCRIPTION OF THE DRAWINGS

[19] These and other features and advantages of the present invention will be made apparent by the following detailed description of some embodiments thereof, provided merely by way of non-limitative examples, description that will be conducted making reference to the annexed drawings, wherein:

[20] **Figure 1** is a schematic diagram showing, partly in terms of functional blocks, an apparatus implementing a method according to an embodiment of the present invention;

[21] **Figure 2** shows in axonometric view a possible practical embodiment of the apparatus shown schematically in **Figure 1**;

[22] **Figure 3** schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a first embodiment of the present invention;

[23] **Figure 4** schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a second embodiment of the present invention;

[24] **Figure 5** schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a third embodiment of the present invention;

[25] **Figure 6** schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a fourth embodiment of the present invention;

[26] **Figure 7** schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a fifth embodiment of the present invention;

[27] **Figure 8** schematically shows, in longitudinal cross-sectional view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a sixth embodiment of the present invention;

[28] **Figure 9** schematically shows, in longitudinal cross-sectional view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a seventh embodiment of the present invention;

[29] **Figure 10** depicts quite schematically another type of radiant combustion reactor adapted to be used in the apparatus of **Figure 1**;

[30] **Figure 11** schematically shows, in axonometric view, a first possible implementation of the radiant combustion reactor of **Figure 10**, in an embodiment of the present invention;

[31] **Figure 12** schematically shows, in axonometric view, a second possible implementation of the radiant combustion reactor of **Figure 10**, in another embodiment of the present invention;

[32] **Figure 13** shows rather schematically, in axonometric view, a third possible implementation of the radiant combustion reactor of **Figure 10**, in still another embodiment of the present invention;

[33] **Figures 14A**, **14B** and **14C** schematically shows, in axonometric view and in cross-section, a first possible implementation of a third type of radiant combustion reactor adapted to be used in the apparatus of **Figure 1**;

[34] **Figure 15** schematically shows, in axonometric view, a second possible implementation of said third type of radiant combustion reactor; and

[35] **Figure 16** schematically shows, in axonometric view, a third possible implementation of the third type of radiant combustion reactor.

DETAILED DESCRIPTION

[36] With reference to the drawings, in **Figure 1** a schematic diagram is provided showing, partly in terms of functional blocks, an apparatus implementing a pollutants-reduction method according to an embodiment of the present invention.

[37] The pollutants-reduction apparatus, denoted globally as **100**, is schematically depicted as placed downstream a block **105**, representative of a generic apparatus of any type whose operation involves the combustion of fuels, particularly fossil fuels such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, coal, wood, and the like, generally any fuel adapted to be used in a combustion process; for example, the apparatus **105** may be an internal-combustion engine of a vehicle, particularly but not limitatively of the Diesel type or based on the Otto cycle, or a burner of a heating system for buildings, or steam boilers for electric power plants. Downstream the pollutants-reduction apparatus **100**, a block **110** is provided, schematically representing an exhaust system of any conventional type, for example a simple muffler of a vehicle.

[38] In greater detail, the pollutants-reduction apparatus **100** has an input manifold **115i**, for receiving combustion exhaust gases from the apparatus **105**; the received exhaust gases are treated by the apparatus **100** before being released in the environment; the pollutants-reduction apparatus **100** has an output manifold **115o** for delivering treated exhaust gases to the exhaust system **110** (it is however observed that the exhaust system **110** might also not be provided for, and the treated exhaust gases be released directly into the environment).

[39] The input manifold **115i** leads the exhaust gases to be treated to a gases pre-heating chamber **120**, where the exhaust gases, received from the apparatus **105** at a relatively low temperature, are submitted to a preliminary heating process. Considering for example the case of exhaust

gases from an internal combustion engine, particularly of the Diesel type, the temperature of the exhaust gases should in theory be around 400 – 450 °C; however, experimental trials conducted by the Applicant have revealed that the exhaust gases temperature is normally lower, falling in the range from approximately 150 °C to approximately 300 °C. The preliminary heating process in the pre-heating chamber **120** brings the exhaust gases temperature to a suitably higher value, preferably a value higher than 400 °C, for example a value in the range from approximately 400 °C to 700 °C and, preferably, from approximately 550 °C or 600 °C to approximately 700 °C.

[40] In an embodiment of the present invention, the pre-heating chamber **120** comprises means adapted to submitting the incoming exhaust gases to a compression, thereby the gases temperature rises. In particular, the pre-heating chamber **120** may comprise means adapted to impart a suitable acceleration to the exhaust gases, and particularly one or more among a fan (or an arrangement of fans), a turbine (or an arrangement of turbines), a turbocompressor; these elements are only schematically indicated in **Figure 1**, and identified therein by **121**. The acceleration imparted to the exhaust gases is preferably such that the gas temperature is raised to approximately 500 °C - 600 °C.

[41] Preferably, downstream the means **121** for accelerating the exhaust gases, a Venturi tube (schematically represented in **Figure 1** and identified therein as **123**) is provided, for further compressing the exhaust gases and thus causing a further increase of the temperature thereof, for example up to a temperature of approximately 700 °C.

[42] From the pre-heating chamber **120**, the pre-heated gases are conveyed to a radiant combustion reactor or radiant combustion chamber **125**, situated just downstream the Venturi tube **123**.

[43] The radiant combustion chamber **125**, several practical embodiments of which will be described in greater detail later on, is a chamber

with walls made of suitable material, which are heated by a heat source to a prescribed temperature, thereby the chamber walls radiate electromagnetic energy within the chamber (in the way that approximate the black-body radiation). Within the radiant combustion chamber **125** the temperature of the exhaust gases is raised further and rather quickly from the pre-heating temperature, for example the initial approximately 700 °C, to a temperature in the range from approximately 900 °C to approximately 1200 °C, preferably from approximately 900 °C to approximately 1100 °C, suitable to determine a combustion (post-combustion) of the exhaust gases; more generally, the upper limit of the temperature of the exhaust gases may be chosen in such a way that, at such a temperature, the creation of nitrogen oxides is not relevant; thus, the maximum temperature of the gases within the combustion chamber **125** may reach 1300 – 1400 °C or even higher temperatures, for example up to 1800 °C. The increase in temperature is achieved by radiant electromagnetic energy, particularly in the wavelength range from IR to UV, radiating from the walls of the radiant combustion chamber **125**. In case no pre-heating is provided for, within the radiant combustion chamber the exhaust gases temperature should be raised from the above-mentioned initial 150 C° – 300 °C to the desired high temperature.

[44] A possible explanation of the exhaust gases temperature increase within the radiant combustion chamber can be found in the radiating effect, according to which the transfer of energy from the walls of the radiant combustion chamber to the exhaust gases is proportional to the fourth power of the temperature in Kelvin degrees.

[45] By subjecting the exhaust gases to such a fast increase in temperature, the exhaust gases post-combustion process that is automatically ignited allows substantially reducing or even eliminating the harmful, uncombusted particulates present in the exhaust gases. In particular, in the exhaust gases, typically being a mix of oxygen, uncombusted hydrocarbons, carbon particulate, self-combustion is automatically ignited, because the

gaseous fluid in the chamber **125** travels in an environment at a temperature which is higher than the self-combustion temperature (the specific value of which depend on the substances present in the exhaust gases), and the combustion is carried out exploiting the radiant energy irradiating from the walls of the chamber **125**. This substantially improves the efficiency of the combustion of the carbon particulates, which is more difficult than that of hydrocarbons because the combustion time is related exponentially to the size and shape of the particle.

[46] It is observed that by ensuring that the gas temperature in the radiant combustion chamber **125** is sufficiently high, in particular higher than approximately 450 °C, preferably in the range from approximately 900 °C to approximately 1200 °C, and more preferably from approximately 900 °C to approximately 1100 °C, or higher, up to 1800 °C (generally, a temperature below the temperature at which nitride oxides start forming), nitride oxides already present in the exhaust gases are reduced. To this purposes, the post-combustion process of the exhaust gases may be combined with known reduction processes, such as the Non-Selective Catalytic Reduction (NSCR) process, in presence of oxygen (by providing a suitable feed of oxygen to the radiant combustion chamber, or the Selective Catalytic Reduction (SCR) process, in presence of a noble catalyst (*e.g.*, platinum), maintained at high temperature by the flow of the exhaust gases. It is pointed out that the NSCR and the SCR processes may be exploited in alternative to one another, or in combination, depending in particular on the structure, *e.g.* on the geometry, of the radiant combustion chamber **125.**

[47] It is also observed that, in the radiant combustion chamber **125**, the post-combustion of the exhaust gases takes place at a constant pressure.

[48] In **Figure 1** the radiant combustion chamber **125** is shown very schematically and it is depicted as a substantially "C"-shaped duct; it is pointed out that this is not to be intended as a limitation to the present

invention; in the following of the present description, the radiant combustion chamber **125** will be described in greater detail, and several possible embodiments thereof will be presented and discussed. In any case, the structure of the radiant combustion chamber **125**, particularly the geometry thereof, shall be such that it is ensured that the exhaust gases are submitted to the radiating energy for a time sufficient to reach the desired temperature, for example a temperature in the above-mentioned temperature range, adapted to induce the post-combustion of the pollutants.

[49] Optionally, a first filtering element **130a** is arranged along the radiant combustion chamber **125** (for example, the radiant combustion chamber **125** may be made up of two parts in cascade, and the filtering element **130a** may be arranged between the first and the second part).

[50] Upon leaving the radiant combustion chamber **125**, the post-combusted exhaust gases are led to a second filtering element **130b**.

[51] Each one or both of the filtering elements **130a** and **130b** may comprise active and/or inactive filters, particularly selective filters, preferably active nanofilters in ceramic/zeolite material, and are used for trapping residual dust and Particulate Material (hereinafter, shortly, PM) still present in the exhaust gases after the post-combustion process in the radiant combustion chamber **125**. An active filter generally acts as a catalyzer with oxidation reactions; active filters typically are based on metals. An inactive filter is essentially a trap. It is observed that using for example zeolite materials, both active and inactive filters can be realized (placing a zeolite in a bath of gold or palladium produces an active filter). In particular, the first filtering element **130a**, if provided, allows trapping the residual, uncombusted dust and PM present in the exhaust gases after a first post-combustion phase, while the second filtering element **130b**, positioned at the output of the radiant combustion chamber **125**, serves for trapping the uncombusted dust and PM still remaining in the exhaust gases after the post-combustion. Depending on

the type of nanofilters adopted, the filtering elements may act both as hot catalysts, and as pure filters,

[52] It is pointed out that the specific arrangement, the number and the dimensions of the nanofilters making up the filtering elements **130a** and **130b** will depend on the specific type of apparatus **105** to which the pollutant-reduction apparatus **100** is intended to be associated with. However, as a general rule, nanofilters resistant to high temperatures should be used.

[53] It is also observed that more than one intermediate filtering element **130a** may be provided along the radiant combustion chamber.

[54] Preferably, the filtering elements **130a** and **130b** are removable from the apparatus **100** and, even more preferably, they are also reconditionable or recyclable.

[55] Optionally, means suitable to favor the exit of the post-combusted gases from the radiant combustion chamber **125** are provided, as shown in phantom and indicated by **127** in **Figure 1**; for example, such means may comprise another Venturi tube, or any other device capable of determining a depression downstream the chamber **125**.

[56] After being passed through the second filtering element **130b**, the treated exhaust gases (substantially freed of the harmful pollutants) are led to a heat exchange arrangement **135**. In the heat exchange arrangement **135** the temperature of the treated exhaust gases is lowered from the approximately 900 °C – 1200 °C to values suitable to avoid thermal shocks, such as a temperature value of approximately 100 °C - 150 °C or lower, from approximately 50 °C – 150 °C.

[57] Expediently, as schematically depicted in the drawing, the heat exchange arrangement **135** is arranged in such a way that at least part of the heat released by the treated exhaust gases is exploited for pre-heating the incoming gases to be treated in the pre-heating chamber **120**, thereby alleviating the burden of the exhaust gases acceleration means.

[58] Preferably, the heat exchange arrangement **135** is made of materials resistant to high temperatures, particularly sodium, lithium, titanium, etc.), and it may be of the molded metal type, of the liquid metal type, of the plate type, of the spiral type; in case the apparatus **100** is intended to be installed on a vehicle, the heat exchange arrangement shall have a suitably compact design.

[59] From the heat exchange arrangement **135**, the treated exhaust gases, from which the harmful pollutants have been substantially eliminated, are led to the output manifold **115o**, and then to the exhaust system **110** (for example, the muffler of the vehicle).

[60] A control unit **140** is provided in the apparatus **100** for controlling the operation of the various components thereof (as schematized by the dash-and-dot lines in the drawing). In particular, the control unit **140** comprises electronic control means, preferably programmable, particularly microprocessor-based control means, adapted to execute suitable microprograms for implementing a predefined control flow, and sensors, such as pressure sensors and temperature sensors for detecting the operating temperature in the different parts of the apparatus **100**, such as the pre-heating chamber **120**, the radiant combustion chamber **125**, the heat exchange arrangement **135**, the pressure and/or velocity of the exhaust gases in different points of the path, and sensors for establishing the percentages of the various pollutants in the exhaust gases. The control unit may control the heating of the radiant combustion chamber.

[61] The specific controls operated by the control unit **140** depend largely on the structure of the radiant combustion chamber **125**, but in general the control unit **140** shall at least ensure that a correct temperature is maintained within the chamber **125**.

[62] **Figure 2** is an axonometric view of a possible practical implementation of the pollutant-reduction apparatus **100**, particularly adapted

to the installation on a vehicle such as a car or a bus. The different parts of the apparatus shown schematically in **Figure 1** and described in the foregoing are identified in **Figure 2** with the same reference numerals.

[63] In the following of the present description, several different embodiments of the radiant combustion chamber **125** will be presented, being however intended that the list of presented alternatives is not to be intended as exhaustive, and several other embodiments can be devised. It is in fact pointed out that the specific spatial configuration and structure of the radiant combustion chamber **125** may depend on the specific application.

[64] In the embodiment shown in axonometric view in **Figure 3**, the radiant combustion chamber **125** comprises a substantially "U"-shaped duct **300**, having a pair of tubes (radiant tubes) **300a**, **300b**, particularly substantially rectilinear, joined to each other and in communication of fluid with one another, so as to define thereinside a path for the exhaust gases, wherein the exhaust gases to be treated, received from the pre-heating chamber **120**, are made to flow. Heating means are associated with the "U"-shaped duct **300** for heating the radiant tubes, for example Joule-effect heaters and, more particularly, a pair of electric resistors **305a**, **305b**, each one associated with a respective one of the two radiant tubes **300a**, **300b** of the "U"-shaped duct **300**; particularly, the two resistors **305a**, **305b** are a spiral resistors, each one wound around the respective rectilinear radiant tube **300a**, **300b** of the duct **300**. The resistors **305a**, **305b** are suitably dimensioned (for example, commercially available resistors of the type Kanthal AM or Kanthal AF are suitable), and can be connected either in parallel or in series; an electrical supply (for example provided by the vehicle battery, schematically indicated in the drawing as **350**, or by an autonomous battery, or by the vehicle alternator) is controlled by the control unit **140** (as schematized in the drawing by a switch **355**). When powered, the heat generated by the resistors by Joule effect heats the radiant tubes, bringing them to a suitable temperature, thereby the tubes radiate electromagnetic energy thereinside.

[65] In the embodiment shown in axonometric view in **Figure 4**, the radiant combustion chamber **125** comprises two substantially "U"-shaped ducts **401, 402**, similar to the single, substantially "U"-shaped duct **300** of the previous embodiment, having respective pairs of substantially rectilinear radiant tubes (only three of which, denoted **401a**, **402a**, **402b**, are visible in the drawing) joined to each other and run through in cascade by the exhaust gases. The two "U"-shaped ducts **401, 402** are associated with heating means, in the form of four electrical resistors (only three of which, denoted **405a**, **405c** and **405d**, are visible in the drawing) particularly spiral resistors that, similarly to the resistors **305a**, **305b** of the previous embodiment, are each one associated with, and particularly wound around, a respective substantially rectilinear radiant tube **401a**, **401b**, **402a**, **402b** of the ducts **401, 402**, so as to cause heating thereof when powered by the, *e.g.*, battery **350**. The resistors can be connected in parallel, or in series, or partly in parallel and partly in series.

[66] The radiant combustion chamber **125** in the embodiment shown in **Figure 5** comprises instead a generically "W"-shaped arrangement **500** of substantially rectilinear radiant tubes **500a, 500b**, **500c** and **500d**, connected in cascade one to another so as to be all run through, in succession, by the flow of exhaust gases received from the pre-heating chamber **120**; similarly to the two previous embodiments, associated with each radiant tube is a respective electrical resistor **505a**, **505b**, **505c** and **505d**, particularly a spiral resistor wound around the tube, for heating the tube by Joule effect. For the sake of simplicity, the electrical supply of the resistors is not expressly shown in the drawing, but it is clear to those skilled in the art that a connection to, *e.g.*, the vehicle battery similar to those of the previous embodiments can be provided for.

[67] The radiant combustion chamber **125** in the embodiment of **Figure 6** comprises again a substantially "U"-shaped duct **600** through which the exhaust gases to be treated are made to flow. However, differently from

the previous three embodiments, the heating means that are associated with the duct **600** are not formed by electrical resistors spirally wound around the substantially rectilinear tubes of the duct **600**, being instead formed by at least one, preferably a pair of radiating panels **605a**, **605b** (one of which shown in phantom, for the sake of clarity of the drawing) preferably in close-packed arrangement, each one having embedded therein a respective, properly dimensioned electrical resistor **607**, preferably arranged according to a winding path; albeit not expressly shown, an electrical supply similar to those shown in the previous embodiments is provided for supplying the electrical resistors **607** embedded in the panels **605a**, **605b**. The duct **600** is thus sandwiched between the two radiating panels **605a**, **605b**, and receives heat therefrom.

[68] A still different embodiment of radiant combustion chamber **125** is the one depicted in **Figure 7**, wherein instead of having a duct for the exhaust gases formed by tubes, the radiant combustion chamber **125** comprises a hollow box-shaped enclosure **700**, for example having either generically rectangular or generically circular cross-section, with an inlet **700i** for receiving the exhaust gases and an outlet **700o** for delivering the exhaust gases. Within the enclosure **700**, a plurality of baffles **710** are provided, arranged so as to define a suitably winding path **715** for the gases from the inlet **700i** to the outlet **700o**. The enclosure **700** is sandwiched between a pair of radiating panels (only one of the two panels, denoted **705a** is shown, for the sake of clarity) with embedded resistors **707**, similar to the panels **605a**, **605b** of the previous embodiment.

[69] **Figures 8** and **9** show in longitudinal cross-section two further possible embodiments of the radiant combustion chamber **125**. In particular, in the embodiment of **Figure 8** the radiant combustion chamber comprises a pair of coaxial ducts **800a** and **800b**; the inner duct **800a** is hollow and communicates at an end thereof opposite to the end receiving the exhaust gases from the pre-heating chamber with the outer duct **800b**; the outer duct

800b is substantially an external lining of the inner duct **800a**, and has thereinside baffles **805** defining a substantially helical path for the gases. A suitably dimensioned spiral electrical resistor **810** is wound around the outer duct **800b**. Around the resistor **810**, a thermally-insulating lining **815** is provided. The exhaust gases are received from the pre-heating chamber **120** and are fed to the inner duct **800a**, through which the gases flows substantially rectilinearly; then, the gases pass into the outer duct **805b**, which is heated by the electrical resistor **810** and wherein the gases flows following a generically helical path, being thus heated to the desired, self-combustion ignition temperature.

[70] It is observed that if, as in the schematic arrangement of **Figure 1**, an intermediate filtering **130a** is provided for, two coaxial ducts **800** can be used, one upstream and the other downstream the filtering element **130a**. Similar reasoning applies also to the previous embodiments, consisting of differently arranged radiant tubes.

[71] In a slightly different way, in the embodiment of **Figure 9** an elongated, generically toroidal body **900**, having either generically circular or rectangular cross-section, has thereinside a generically helical duct **903** for the gases. The toroidal body **900** is heated by two electric resistors, an inner resistor **910a** and an outer resistor **910b**, particularly spiral resistors; the inner resistor **910a** is inserted in the central cavity of the toroidal body, while the outer resistor **910b** is externally wound around the toroidal body **900**; the two resistors are substantially coextensive to the toroidal body. The exhaust gases flow through the helical duct **903**, and are heated by both the inner and the outer resistors.

[72] Clearly, in both the two latter embodiments a resistor supply arrangement should be provided for, for example similar to those described in connection with the first embodiments presented.

[73] It is observed that the specific dimensions and the material of the ducts (*e.g.* the radiant tubes) making up the radiant combustion chamber **125** depend on the specific application; suitable materials that can be used for realizing the radiant ducts are for example INCONEL (an alloy containing tungsten and manganese) and ceramic. Radiant tubes are also commercially available.

[74] It is observed that the resistor power supply, controlled by the control unit **140**, should preferably be controlled so as to track changes in operating conditions, particularly of the apparatus **105**. For example, in some applications, such as in the case of vehicles, an increased flow of exhaust gases inside the radiant combustion chamber **125** in consequence of, *e.g.*, an acceleration of the vehicle, will require a possibly fast adaptation of the power delivered by the heating resistances, so as to maintain the temperature within the chamber **125** in the desired range.

[75] In order to avoid dispersions of energy, the radiant combustion chamber **125** is preferably thermally insulated (this has been schematically depicted in the embodiments of **Figures 8** and **9**: equivalent thermal insulation should preferably be provided also in the embodiments of **Figures 3** to **4**, albeit not expressly shown in the respective drawings), for example by means of refractory silicon-ceramic materials, or other suitable materials.

[76] The embodiments of radiant combustion chamber **125** described up to now, albeit differing from each other in spatial configuration, are all based on a common, similar heating principle, involving the use of electric resistances as Joule-effect heaters.

[77] Hereinbelow, some further embodiments of the radiant combustion chamber will be presented which are based on a different heating principle.

[78] In detail, instead of using Joule-effect heaters and, particularly, electrical resistors, one or more optical radiation source, particularly one or

more lasers are exploited for triggering the radiant reactor, *i.e.* for heating the radiant combustion chamber to the desired temperature.

[79] Lasers are more and more widely exploited in several applications, either in industry and in consumer products, thanks to the fact that the emitted optical radiation has is very homogenous and concentrated, and that they have a very fast response.

[80] **Figure 10** shows schematically a radiant combustion chamber **125** of the type exploiting optical radiation, generated by a suitable source such as a laser, as a heater.

[81] In detail, the radiant combustion chamber **125** comprises a combustion reactor enclosure **1000**; the spatial configuration of the combustion reactor enclosure **1000** is not limitative to the present invention, depending for example on the specific application: thus, in **Figure 10** the combustion reactor **1000** is schematically depicted as generically elliptical. The combustion reactor **1000** has walls **1005** made of suitable material, for example INCONEL steel, a composite material having a ceramic matrix, or special alloys, adapted to radiate heat when properly heated, and receives thereinside the exhaust gases to be treated.

[82] Outside of and around the combustion reactor **1000**, an arrangement of optical radiation reflecting/deflecting elements **1010** is provided, such as mirrors and/or optical prisms, schematically depicted in the drawing as the internal faces of walls of a box-shaped casing **1007** containing the combustion reactor **1000**.

[83] The arrangement of optical radiation reflecting/deflecting elements **1010** reflects/deflects optical radiation **1015** which is generated by one or more optical radiation sources, particularly lasers, schematically indicated in the drawing at **1020**. It is observed that the number and the arrangement of the lasers **1020** is not limitative to the present invention, depending for example on the shape of the combustion reactor **1000**; in the

drawing, just by way of example, four lasers **1020** are shown, each one located at a respective corner of the box **1007**; the lasers **1020** may be fixed or movable, for example they can be partially rotate and/or be angularly oriented.

[84] The optical radiation emitted by the laser(s) **1020**, controlled by the control unit **140**, is reflected/deflected by the optical radiation reflecting/deflecting elements **1010**, and hits the external side of the walls of the combustion reactor **1000**, causing a substantially uniform heating thereof. In this way, the walls of the combustion reactor are brought to the radiative temperature, *i.e.* to a temperature such that a sufficient electromagnetic energy is radiated from the walls of the combustion reactor into the enclosure **1000.**

[85] In the following, some possible practical embodiments of radiant combustion chamber **125** exploiting the optical-based heating mechanism, particularly the laser-based heating, will be presented, being intended that such embodiments are mere examples.

[86] In particular, in the embodiment schematically shown in **Figure 11** the radiant combustion chamber **125** comprises a radiant tube **1100**, of suitable material, arranged so as to be traversed by the exhaust gases coming from the pre-heating chamber **120**. Outside the radiant tube **1100**, a light reflecting arrangement **1105** is provided, schematically depicted as an outer tube coaxial and coextensive to the radiant tube **1100** and having internal light-reflecting walls. The light reflecting tube **1105** reflects the laser radiation **1110**, generated by a laser **1120**, onto the radiant tube **1100**, thereby causing the heating thereof to the required temperature. The laser **1120** is shown schematically as moving along the axis of the radiant tube; for example, the laser **1120** may be mounted to a carriage. The laser **1120** might also be caused to revolve around the tube **1100**.

[87] It is observed that in **Figure 11** (and in the following drawings) a supply of oxygen (O_2) and ammonia (NH_4) into the tube **1100**, *i.e.*, into the radiant combustion chamber, is schematically shown; this supply, which is optional and could as well be provided in any one of the radiant combustion chamber embodiments described in the foregoing, serves for enabling an NSCR process for reducing nitrogen oxides during the post-combustion of the exhaust gases.

[88] A slightly different arrangement is schematically depicted in **Figure 12**, wherein the radiant combustion chamber **125** comprises a lined radiant tube **1200** having an inner hollow body **1200a** surrounded by an outer hollow body **1200b**, and wherein the exhaust gases are made to pass in the space **1203** between the inner and the outer hollow bodies, whilst a laser **1220** is arranged inside the inner hollow body **1200a**, and the latter has reflecting walls adapted to reflect the laser radiation. Also in this case, the laser **1220** is schematically depicted as movable along and rotatable about the axis of the inner hollow body **1200a**.

[89] **Figure 13** shows quite schematically a still different embodiment of the radiant combustion chamber **125**, having a substantially spherical shape, within which the exhaust gases to be treated are conveyed. The laser(s) **1320** is arranged externally to the spherical reaction chamber, and is for example movable so as to hit different areas of the surface thereof; for example, the laser(s) is associated to moving means suitable to cause the laser to revolve around the reaction chamber, so that the laser radiation hits different points of the chamber external surface and causes a substantially uniform heating thereof.

[90] The substantially spherical shape of the combustion chamber **125** in the embodiment of **Figure 13** allows achieving a high effectiveness in the heating of the exhaust gases conveyed thereinto. In fact, the incoming exhaust gases, at a lower temperature, force the gases already undergone to

the post-combustion process to leave the reaction chamber. Also, albeit not shown in the drawing, an optical radiation reflecting/deflecting arrangement may also in this case be provided for.

[91] It is observed that by properly disaligning the inlet and the outlet of the gases into/from the reaction chamber, a vortex can be created inside the reaction chamber that, proximate to the chamber outlet, optimizes the gas recirculation, favoring the exit of the portion at a higher temperature. This is further helped by the Venturi accelerator **127** that may be placed at the exit of the chamber.

[92] The use of one or more lasers for heating the radiant combustion chamber has the advantage of allowing a substantial reduction in the dimensions of the combustion reactor, because when turned on the laser(s) cause the reactor walls to almost instantly reach the desired operating temperature (necessary for inducing self-combustion of the exhaust gases), and, similarly, the laser(s) can be turned off almost instantaneously.

[93] A suitable number of sensors may be associated with the walls of the radiant combustion chamber so as to enable the control unit **140** causing the laser radiation to hit the desired areas of the radiant combustion chamber walls, scanning the surface according to prescribed patterns in such a way as to cause the surface be homogeneously hit.

[94] In particular, a specific control software may be executed by the control unit **140**, according to which the surface to be hit by the laser radiation is subdivided according to several different parameters, such as the temperature of the areas already hit by the radiation, the difference in temperature between these areas and those not yet hit (the cold areas), the target temperature. A dynamic temperature map is thus built, and such a map, in addition to being used by the control unit to control the laser, might also be displayed, on suitable display devices, to an operator, so as to enable constantly control the operation of the apparatus.

[95] The control software may be based on variation calculations or on perturbation calculation, or on a simpler “fork shoot” (a term derived from the navy jargon and indicating a successive approximation process).

[96] Moreover, the use of laser(s) allows a better controllability of the whole post-combustion process. In fact, by properly driving the pulsed laser(s) through the suitably programmed control unit, the post-combustion process of the exhaust gases can be controlled finely in dependence of the density of the exhaust gases and their velocity, which in turn depend on the engine’s RPMs and on the engine operating temperature.

[97] Additionally, the use of laser(s) reduces the energy consumption, because only relatively high peak energies are required.

[98] The use of lasers thus allows reducing the operation costs.

[99] Those skilled in the art will readily understand that the lasers used, and their optical power, may vary depending on contingent needs, according to the specific applications. The laser(s) may be operated in Continuous Wave (CW) mode or, preferably, in pulsed mode. also, the laser(s) may be of rotating type, or a laser(s) emitting multiple beams properly out-of-phase.

[100] The embodiments shown schematically in **Figures 14A, 14B and 14C**, in **Figure 15** and in **Figure 16** relates to radiant combustion chambers within which movable means are provided for propelling the gases during the post-combustion process and/or for varying the internal geometry of the radiant combustion chamber during operation. It is pointed out that these, and other equivalent solutions, may be adopted in either a Joule-effect heated reaction chamber, or in a radiant combustion chamber heated by optical radiation, and in general in any type of radiant combustion chamber, irrespective of the heating means.

[101] In particular, in **Figures 14A, 14B** and **14C** there is schematically shown, in axonometric and cross-sectional views, a substantially cylindrical

radiant combustion chamber **1400** (depicted as transparent, for the sake of clarity) with a tri-lobes rotor **1405** rotatably inserted therein, having lobes **1405a**, **1405b**, **1405c** angularly spaced of approximately 120° from each other, and with different possible cross-sectional areas, as visible in the cross-sectional views of **Figures 14B** and **14C**.

[102] A suitable drive arrangement is also provided, not shown in the drawings, for causing the rotor **1405** to rotate about its axis inside the chamber.

[103] If, for example, a laser source is used for heating the radiant combustion chamber, as in the embodiment of **Figure 11** the laser radiation hits the chamber from the outside thereof. Alternatively, the radiant combustion chamber **1400** may be a radiant tube similar to the radiant tubes of the embodiments of **Figures 3** to **6**, and in this case the heating means may comprise a spiral electrical resistor wound around the chamber **1400**, or one or two heat radiating panels with electrical resistors embedded therein.

[104] The exhaust gases to be treated are conveyed into the chamber through an inlet **1410i**; within the radiant combustion chamber, the rotation of the rotor **1405** causes a dynamic partition of the internal space of the chamber into three dynamically-varying portions, and facilitates the flow of the gases towards an outlet **1410o** or **1400o'**; while flowing from the inlet to the outlet, the gases undergoes a post-combustion process due to the radiant energy radiating from the walls of the chamber **1400**.

[105] It is observed that the inlet **1410i** and the outlet **1410o** or **1400o'** to/from the radiant combustion chamber can either be axially aligned or not, and either the inlet or the outlet **1410o** or **1400o'** or both may even be perpendicular to the chamber axis. As mentioned in the foregoing, **Figures 14B** and **14C** show possible different shapes of the rotor **1405**, differing from each other for the cross-sectional area. Other shapes are clearly possible.

[106] In the embodiment of **Figure 15**, a rotor **1505** constituted by an endless screw is rotatably arranged within the cylindrical radiant combustion chamber **1400** (depicted again as transparent, for clarity); a suitable drive arrangement, not shown in the drawing, is provided for rotating the rotor **1505**. Also in this case, the cross-sectional shape of the rotor can vary so as to vary the internal volume of the post-combustion chamber, in dependence of the specific application.

[107] Finally, in the embodiment of **Figure 16** a spherical reaction chamber **1600** is provided (shown in the drawing in sectional view along a diametral plane), instead of a cylindrical one, and an internal rotor **1605** is rotatably arranged within the spherical reaction chamber **1600**. The rotor **1605** has a generically spherical shape, with three substantially hemispherical depressions **1605a**, **1605b** and **1605c**, the rotor **1605** is thus shaped so as to define three post-combustion chambers within the chamber **1600**, of suitable volumes.

[108] As already pointed out, the embodiments shown in **Figures 14A**, **14B**, **14C**, **15** and **16** do not necessarily require the use of a laser(s) as a heating means, being possible to exploit them in connection with more conventional heating means, such as Joule-effect heaters (electric resistors). However, when used in association with a laser, the proper control of the motion of the rotors may optimize the efficiency of the laser pulses.

[109] The Applicant has found that thanks to the method and apparatus of the present invention, approximately 90% of the carbon monoxide, carbon particulate, uncombusted hydrocarbon (C_xH_y) are eliminated from the exhaust gases, and nitrogen oxides (NO_x) are reduced of almost 90%.

[110] The method and apparatus according to the present invention find application in any system wherein combustion of fuels is provided for, such as for example internal-combustion engines, using Diesel fuel, gasoline, methanol, mix of alcohols, natural gas, LPG, Kerosene, fuel oil, hydrocarbons

mixed with water, GECAM, BLUDIESEL, fuel for planes with additives, masut for marine engines.

[111] It is observed that the post-combustion process carried out in the radiant combustion chamber may be either continuous, partially continuous or discontinuous (intermittent). By continuous there is intended a process wherein there is no substantial separation between the incoming, relatively cold exhaust gases to be treated and the outgoing, hot and already treated exhaust gases: the cold phase is contiguous to the hot phase. A partially continuous post-combustion process is one in which there is a certain separation in time (for example, of the order of 10^{-6} to 10^{-2} seconds) between the cold and the hot phases, *i.e.* between the cold and the hot gases; this is for example the case where a combustion chamber such as those of the embodiments of **Figures 14A, 14b, 14c, 15** and **16** is used, wherein the provision of the internal rotor allows for a certain separation of the cold gases from the hot gases. A discontinuous or intermittent post-combustion process is instead one in which the post-combustion chamber is loaded with gases, then the chamber is closed, the post-combustion process is carried out, the chamber is opened to discharge the treated gases, and then the process is re-started.

[112] It is pointed out that the method and apparatus according to the present invention can be used in conjunction with other known pollutants-reduction methods and apparatuses, particularly those directed to eliminating nitrogen oxides (NO_x), such as Ignition Time Retardation (ITR), advanced systems of reactant injection, such as the RJM Aris™ technology, water injection, emulsions, turbocompressed air, air mixed to a fuel, Exhaust Gas Recirculation (EGR) systems, introduction of refrigerated air, high injection pressure and change of air/fuel proportion, a turbo composite, and the like. In particular, all these known techniques are preferably implemented downstream the apparatus of the present invention.

[113] The method and apparatus of the present invention can also be used in conjunction with the known devices for eliminating sulphur oxides, particularly sulphur dioxide (SO_2) and sulphuric oxide (SO_3).

[114] The apparatus according to the present invention can take the form of a kit ready to be installed on a vehicle, as a retrofit

[115] The method and apparatus according to the present invention are capable of reducing substantially the emissions of vehicles propelled by internal-combustion engines, and also hybrid-propulsion vehicles, with both electrical and internal-combustion propulsion, will greatly benefit of the apparatus.

[116] Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.

[117] For example, other types of radiant combustion chamber might be exploited, particularly radiant combustion chambers provided with different heating means, such as gas burners.